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Issue Paper 3

Spatial and Temporal Patterns of Stream Temperature (Revised)

Prepared as Part of EPA Region 10 Temperature Water Quality Criteria Guidance Development Project

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Note: Minor revisons have been made to this document from its original June, 2001 version. These revision were made in response to public comment. Several commentors were confused by specific sections of this document and/or questioned whether some discussions were appropriate. The revisions are an attempt to clarify, not alter, the original intended message. To facilitate comparison with the original document, modified paragraphs are marked with a light shaded background (as used here).

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Geoffrey Poole, John Risley, and Mark Hicks

Abstract

Stream temperature is an aspect of water quality that affects every aquatic organism. Yet taking that temperature is not as easy as it may seem. Placing a thermometer in a stream and recording the reading are simple enough. The problem is that the result does not represent the entire stream, whose temperatures vary markedly over both time and location. Instead of a single measurement, what is needed is a set of measures that describes a stream's "temperature regime." Even then, the process is complicated. Many factors affect the temperature regime, including climate, riparian or stream bank vegetation, and channel form and structure. The factors with the strongest influence vary from time to time and place to place. What's more, patterns of variation in stream temperature differ depending on the timescale of observation and the size of the area within which temperature is measured. For instance, variation in stream temperature over a single day is apt to differ from variation over an entire year. Similarly, the patterns of temperature observed within a single pool or riffle in a stream are apt to differ completely from the patterns observed along the entire stream course. Stream temperature regimes are difficult to quantify, but available evidence suggests that stream temperature regimes in the Pacific Northwest are now typically different from those that existed before Euro-Americans settled the region. Evidence further shows that a variety of human activities often are responsible for changes in temperature regimes over time and that the effects of human activities often are cumulative: individual land use activities that alone would not substantially alter stream temperature can do so when combined with other activities or with natural disturbances. Alteration of these regimes in turn may contribute to a decline in the family of fish known as salmonids, which until recently has successfully adapted to historical variations in stream temperature. In many streams where large salmon runs once were typical, the temperature regimes now appear inhospitable. Thus, from a scientific perspective, restoration of temperature regimes compatible with desired populations is an important factor in their recovery.

Introduction

Water temperature dynamics in Pacific Northwest streams are complex. Water temperature varies from place to place within a stream network, and, at any place, water temperature is variable over time. Temperature dynamics have ultimately played an important role in the life history of Pacific Northwest salmonids. Salmonids have developed physiological (see Physiology issue paper) and behavioral (see Behavioral issue paper) adaptations to temperature dynamics that have allowed them to thrive in the rivers and streams of the Pacific Northwest even though stream temperatures may never have been optimal in all places and at all times. Where humans have caused changes to temperature dynamics is streams, however, the changes have often been too rapid and widespread for salmonids to flourish. Although many factors have contributed to the decline in native salmonid populations, temperature has had an important role (see Distribution issue paper). Additionally, although other factors have contributed to native salmonid declines, many of these factors (such as disease or habitat loss) are exacerbated by human-caused changes to stream temperature dynamics (see Multiple Stressors issue paper).

In this paper, we answer common questions about water temperature dynamics in the Pacific Northwest. In answering these questions, we attempt to portray the complexity of water temperature dynamics in Pacific Northwest streams and highlight the variety of ways in which human actions can influence stream temperature. The paper also attempts to provide a conceptual framework upon which the interacting roles of physiology, behavior, and multiple stressors can be integrated into a more realistic understanding of the importance of stream temperature to Pacific Northwest salmonids.

What does "stream temperature" measure?

Temperature is a measure of the concentration of heat energy in water. Therefore, when heat is added to a given volume of water, the temperature increases. When heat is lost, the temperature decreases. Furthermore, a given amount of heat will increase the temperature of a small volume of water more than it will the temperature of a large volume of water. This is because the heat energy is more diluted in a large volume of water, and, therefore, the concentration of heat energy is lower.

The initial temperature of the stream at its headwaters and the amount of heat added to or lost from the stream determine the temperature of a stream. Many different factors influence the initial temperature of the stream and the rate at which heat is added to or lost from the stream (Poole and Berman in press).

What is a "temperature regime"?

Stream temperatures are dynamic over space and time. Summertime stream temperatures are warmer than wintertime temperatures, and, even on the same day, a stream's temperatures at noon might be substantially warmer than in the middle of the night. At any given time, a stream will have different water temperatures at different locations. Because of the numerous factors that can influence water temperatrues, temperature patterns vary both within and among streams. In some streams, for instance, daily temperature fluctuations may be reduced by vegetation that shades and insulates the stream or by influxes of groundwater that cool the stream. In other streams where groundwater inputs and shade are not common, daily temperature fluctuations may be greater. (For more information on temperature dynamics in the Pacific Northwest, see Coutant 1999.)

Because of the dynamic nature of temperature in streams, it is difficult to talk about a stream's temperature as though it could be represented by a single value. Therefore, it can be helpful to think of stream temperature in terms of a "temperature regime." A regime includes the concepts of magnitude, frequency, duration, timing, and rate of change. Therefore, a temperature regime describes the distribution of the magnitude of stream temperatures, the frequency with which a given temperature occurs, the time of the day or year when a given temperature occurs, and the duration of time for which a stream is above or below a given temperature. Temperature regimes can be summarized and quantified using statistics that describe distributions (Figure 1). The mean, median, maximum, minimum, and variance can all be used to describe a temperature regime for a given length of stream over a given period of time. Measures of the time and location at which mean, maximum, and minimum temperatures occur are useful as well.

What influences a stream's temperature regime?

Stream temperature regimes are influenced by processes that are external to the stream as well as processes that occur within the stream and its associated riparian zone. Many of the external factors influencing stream temperature are listed in Table 1. These factors influence how heat is delivered to or removed from the stream system and affect stream temperatures in various ways. During the day, the sun warms streams; at night, streams cool down (Beschta 1997, Webb and Zhang 1997). In the winter, streams are colder, and the difference between daily maximum and minimum is generally less than in the summer. The presence or absence of cloud cover and the relative humidity in the air also affect daily stream temperature regimes. Similarly, at points where groundwater enters a stream, the temperature of the stream is buffered against extremes because groundwater temperatures tend to be relatively constant throughout the year.

Other factors associated with the physical structure of the stream itself (Table 2) affect stream temperature (Beschta et al. 1987, Webb and Zhang 1997). For instance, vegetation that shades the stream can reduce fluctuations in stream temperature over the day. The shape of the channel can also affect the temperature—wide shallow channels are more easily heated and cooled than deep, narrow channels. Another important factor influencing stream temperature regimes is the amount of water in the stream. Streams that carry large amounts of water resist heating and cooling, whereas temperature in small streams can be changed easily.

In short, temperature regimes are influenced by (a) the processes that deliver heat to and remove heat from the stream, (b) the characteristics of the channel through which the stream flows, and (c) the physical characteristics of the stream itself. (For a more detailed discussion of the influence of external factors and internal structures on stream temperature, see Poole and Berman in press.)

Specifically, what internal stream characteristics influence stream temperature regimes?

The general structure of a stream system is represented in Figure 2. Note that a stream comprises more than just the stream channel. A stream's components include the riparian vegetation, floodplain, channel, and alluvial aquifer (Ward 1997). "Riparian vegetation" refers to these plants that grow close to a stream, where the stream influences the growing conditions (e.g., by providing water to the plants) (Gregory et al. 1991). Because growing conditions near the stream are different from those further away from the stream, the riparian vegetation often comprises different species of plants from those growing further away from the stream. The "floodplain" is the land area along the stream subject to occasional or frequent flooding (Ward et

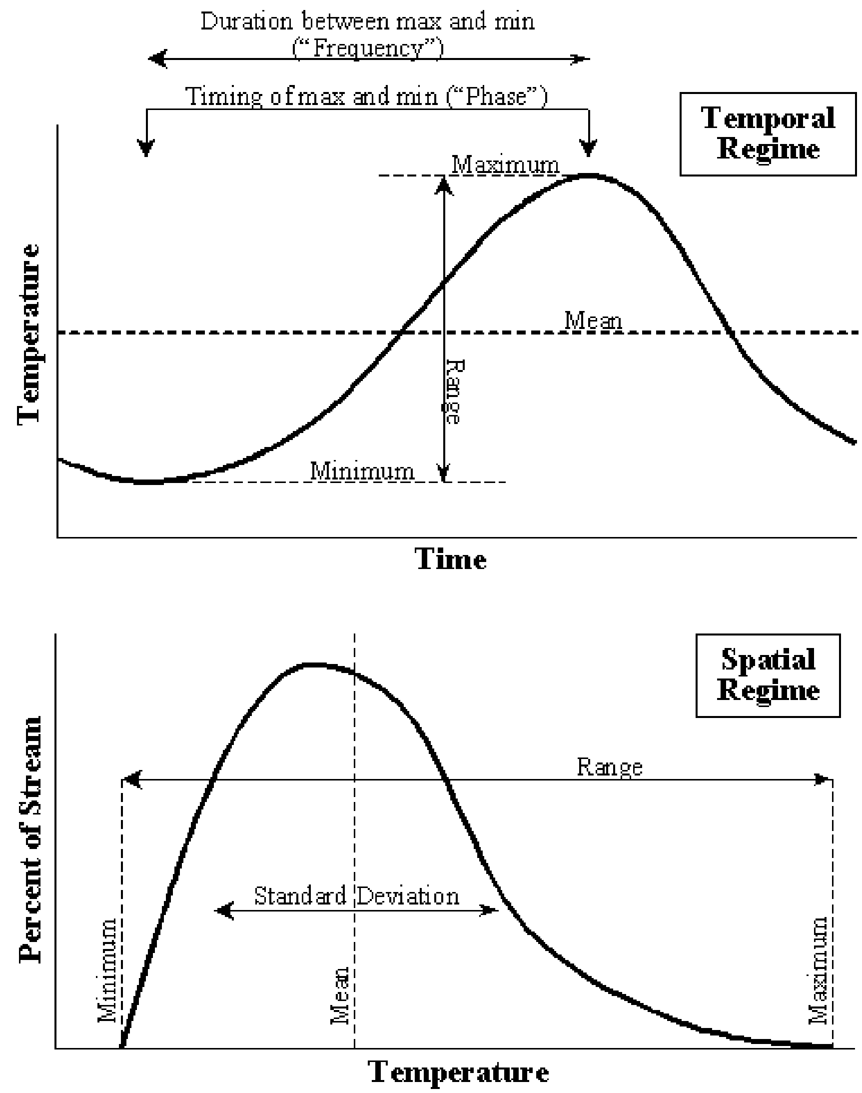

Figure 1. Some metrics used to describe temperature regimes. This figure represents a partial list of common metrics that could be used to describe temperature regimes, not a comprehensive collection of all metrics. Other metrics not illustrated here could be appropriate for describing temperature regimes for various specific purposes.

Table 1. Examples of factors external to the stream that can affect channel water temperature

Topographic shade	Solar angle
Upland vegetation	Cloud cover
Precipitation	Relative humidity
Air temperature	Phreatic groundwater temperature and discharge
Wind speed	Tributary temperature and flow

Source: Poole and Berman in press.

Table 2. Stream structures that influence insulating and buffering characteristics

Component	Characteristic	Determined by	Ecological influence over
Channel			
	Channel slope	Catchment topography	Flow rate
	Channel substrate	Flow regime, sediment sources, stream power	Groundwater flow resistance Channel roughness and therefore flow rate and thermal stratification
	Channel width	Flow regime, sediment sources, stream power, bank stability	Surface area for convective heat exchange
	Streambed topography	Flow regime, sediment sources, stream power, bank stability, large roughness elements (e.g., large woody debris)	Gradients that drive hyporheic flux
	Channel pattern	Flow regime, sediment sources, stream power, bank stability, large roughness elements, valley shape	Gradients that drive hyporheic flux Potential shade from riparian vegetation
Riparian zone			
	Riparian vegetation	Flow regime, vegetation height, density, growth form, rooting pattern	Shade to reduce solar radiation Wind-speed, advective and conductive heat transfer Bank stability
	Riparian width	(same as channel pattern)	Potential for hyporheic flux Potential for shade
Alluvial aquifer			
	Sediment particle size	(same as channel substrate)	Potential for hyporheic flux
	Sediment particle sorting	(same as channel substrate)	Diversity of subsurface temperature patterns by determining stratigraphy Extent of hyporheic flux
	Aquifer depth	(same as channel pattern)	Extent of hyporheic flux

Source: Poole and Berman in press.

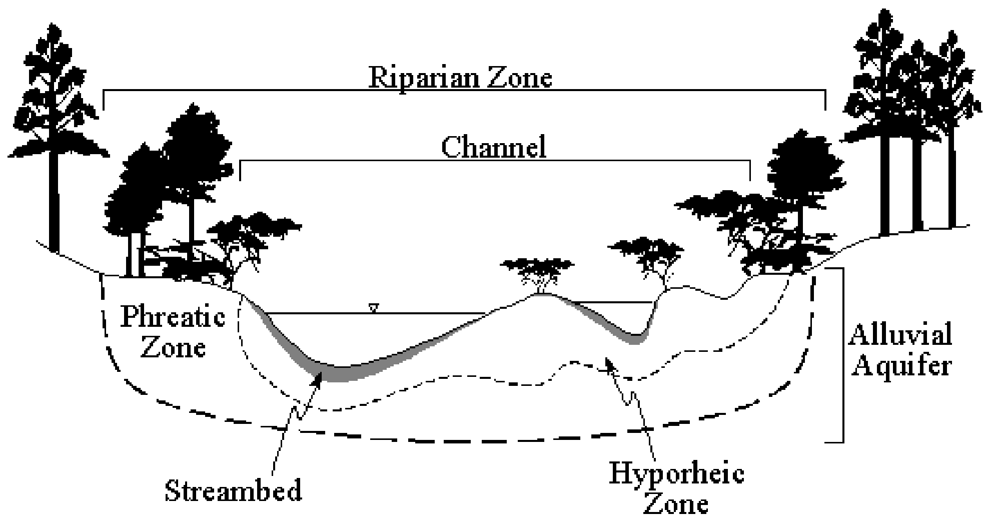

Figure 2. Structural components of a stream system (after Poole and Berman in press).

al. 1999). For our purposes it is roughly that land area that is capable of supporting riparian vegetation. The "stream channel" is the area wetted at least once during the year during high water. The stream bank defines the edge of the channel. For our purposes, we will consider the channel to include side channels, seasonal channels (those channels that flow only during high water periods), ox-bow ponds, and other areas of the floodplain dominated by surface water. Finally, the *alluvial aquifer* comprises the groundwater contained in the sediments that have been laid down over time by the river. In some streams, the alluvial aquifer extends for miles from the river. In other streams, the alluvial aquifer is limited to the water contained in the streambed sediment.

Each of these stream components can influence stream temperature regimes. Riparian vegetation can shade a stream channel and trap cool air around it (Beschta 1997, Johnson and Jones 2000), although exposed channels may have offsetting increases in evaporative heat loss. Thus, riparian vegetation insulates the water in the stream channel. The alluvial aquifer may exchange water rapidly with the stream channel. Water that has entered the alluvial aquifer from the channel is known as "hyporheic water," and the portion of the aquifer that contains a substantial amount of hyporheic water is called the "hyporheic zone." Significant hyporheic flow (the movement of water from channel to hyporheic zone and back) can act as a strong buffer against changes in water temperature (Poole and Berman in press).

The shape of the floodplain and channel influences stream temperature regimes in various ways. As mentioned above, the width and depth of a stream are important. Additionally, the complexity of the channel and presence of secondary channels affect the temperature regime (Cavallo 1997). Complex channels with backwaters, shallow margins, deep pools, side channels, and so on, have more diverse temperature regimes (Beschta et al. 1987, Beschta and Platts 1986, Evans and Petts 1997, Poole and Berman in press), whereas simple uniform channels have simplified temperature regimes.

Which stream characteristic influences on temperature regimes the most?

No particular stream characteristic is the most important in all places. The relative importance of different dynamics changes depending on the characteristics of the stream. Table 3 provides a simple example for streams of different sizes, although the dynamics described in Table 3 are generalities, not hard and fast rules.

What is meant by "spatial scale" and "temporal scale"?

Spatial scale refers to the physical size of a system being considered in a scientific study and temporal scale refers to the time period over which the study takes place. In any natural system, some processes occur rapidly and within very small areas, such as the spawning behavior of a
particular pair of fish. Other processes occur over long periods of time across large areas, such as the spawning of entire fish populations. It is important to match the scale of a scientific research project to the scale of the process being studied; otherwise, there is a high risk of obtaining incorrect results from the research. Studies that attempt to quantify temperature regimes will obtain results that depend on the scale of the research. (For a more complete discussion of the concepts of scale and hierarchy and their application to ecological systems, see Allen and Starr [1982]).

Table 3. Relative influence of stream characteristics on thermal regime in headwater streams (1st and 2nd order), major tributaries (3rd and 4th order), and mainstem rivers (5th order or greater)

	Stream Characteristics				
Stream Order	**Riparian Shade**	**Stream Discharge**	**Tributaries**	**Phreatic Groundwater**	**Hyporheic Groundwater**
1-2	High	Low	Moderate	High	Low - Mod
	Riparian shade and lateral phreatic groundwater inputs provide thermal stability. Lateral tributaries can frequently affect overall stream temperature. Large wood stores sediments and creates streambed complexity, driving hyporheic flow. (However, hyporheic influence is "High" and shade "Moderate" in alpine meadow systems.)				
3-4	Moderate	Moderate	High	Moderate	Mod - High
	Temperature of lateral tributaries has strong influence on stream temperature. Effects of riparian shade modest. Thermal inertia due to larger flows becomes more important. Where floodplains form, channels patterns become more complex, and alluvial aquifers are well developed, hyporheic influence can be high. Large wood creates habitat complexity and forms channel-spanning jams that may provide significant shade to the stream.				
5+	Low	High	Low - Mod	Low - Mod	Mod - High
	Complex floodplain morphology creates a diversity of surface and subsurface flow pathways with differential downstream flow rates allowing for stratification, storage, insulation, and remixing of waters with differential temperatures. The resulting mosaic of surface and subsurface water temperatures continually remix to buffer channel temperature and create thermal diversity. The thermal inertia of large water volumes allows the stream to resist changes in temperature. Where side channels exist, shade from vegetation can be important.				

Source: Poole and Berman in press.

How are the concepts of spatial and temporal scale relevant to temperature regimes?

Water temperature varies across both space and time at several scales. Temperature regimes can be used to describe dynamics across space at various scales: (a) between stream catchments (the areas drained by the stream), (b) between stream reaches, and (c) within stream reaches. Similarly temperature regimes can be used to describe temperature dynamics over time at various scales: (a) from year to year (interannually), (b) seasonally, and (c) daily. Note that the statistical terms used to describe temperature regimes (mean, maximum, minimum, etc.) have different values depending on the spatial and temporal scale. Because temperature regimes differ across scales, regimes must be classified by their spatial and temporal scale in order to be most useful (Table 4).

How are scale-specific temporal regimes important to salmonids?

At coarse temporal scales, climatic variation from year to year (i.e., interannually) is typically reflected in inter-annual stream temperature regimes. Unlike variation in temperature across seasons, interannual variation is relatively unpredictable. Year-to-year variation provides the annual "baseline" temperature around which temperatures deviate at smaller temporal scales and across space. In other words, metrics such as daily or seasonal mean, maximum, and

Table 4. Temperature regimes at different spatial and temporal scales

Temporal Regimes	
Daily regime	Cyclical patterns of temperature over a day characterized by the timing and magnitude of maximum afternoon and minimum nighttime temperature and by the number of minutes spent at each temperature in between.
Seasonal regime	Cyclical patterns of temperature across a year characterized by timing and magnitude of maximum summertime and minimum winter temperature and the number of days spent at each time in between.
Interannual regime	Predominantly unpredictable variation in temperature from year to year. Includes the concept of “hot/dry” and “cool/wet” years. Describes climatic extremes and expected seasonal temperatures.
Spatial Regimes	
Reach-scale regime	Variation in stream temperature due to geomorphic variation at fine scales such as pools, riffles, backwaters, etc. Temperature variation at this scale provides pockets of cool water (“micro-refugia”) used by fish to avoid thermal stress of exposure to warm water.
Segment-scale regime	Variation in mean stream temperature between stream reaches. May be driven by changes in stream valley geomorphology and channel pattern along the stream profile. Cool reaches provide staging areas for migrating salmonids. Loss of variability at this scale may result in “warm at the bottom/cool at the top” streams.
Catchment-scale regime	Variation in mean temperature between stream basins. Includes the concept of “mountain streams” and “desert streams.” Driven by differences in climate, geography, topography, and vegetation between basins.

minimum are all influenced by year-to-year climatic variation. For instance, in warm/dry years, streams in high desert basins or in the southern end of salmonid ranges may be relatively inhospitable for salmonids because thermal stresses are especially high. Similarly, in cold/wet years, these normally marginal streams may provide an excellent habitat in terms of stream temperature. Because predictable patterns are lacking for interannual variation in stream temperature, salmonids have few physical or behavioral adaptations that allow individual fish to compensate or take advantage of variation at this scale. Instead, the broad distribution of salmonids throughout the Pacific Northwest (see Distributions issue paper) has allowed populations to remain robust in spite of both interannual climate variation and historical trends in regional climate (Lichatowich 1999). Trends in year-to-year variability (e.g., global climate change), however, may have a significant effect on the freshwater portion of the salmonid life cycle, including changes in the timing of runs, size of spawning fish, and patterns of smolting (Mangel 1994).

Seasonal variation in stream temperature occurs in a manner similar to changes in annual air temperature. Both patterns are driven by seasonal cycles of day-length and incoming solar radiation. Thus, streams are generally coldest in the winter and warmest in the summer. These predictable patterns of thermal variation encourage salmonids to exploit different habitats at different times of the year (see Behavior issue paper). In fact, the various types of salmonid behavior life histories can be viewed as different strategies to align seasonal variation in habitat to the habitat requirements of each life stage of the fish (Thompson 1959). This suggests that predictable patterns of seasonal variation in habitat conditions (including temperature) are responsible for and ultimately support the diversity of life history strategies found in salmonids native to the Pacific Northwest.

Daily fluctuations in stream temperature often follow daily fluctuations in solar heating (Stoneman and Michael 1996, Webb and Zhang 1997), with the warmest summertime stream temperatures typically occurring in mid- to late afternoon. These afternoon water temperatures may reach levels that are stressful or even lethal for salmonids. Again, however, the predictability of these patterns allows salmonids to adapt their behavior (e.g., feeding behavior, "staging" in cold water pockets during migration, or migrating at night) (see Behavioral issue paper) to avoid undesirable temperatures.

How are scale-specific spatial regimes important to salmonids?

At coarse spatial scales, water temperatures vary between stream catchments based on catchment characteristics such as elevation, drainage area, morphology, aspect, and lithology (Collins 1973, D'Angelo et al. 1997, Dyar and Alhadeff 1997, Hawkins et al. 1997, Moore 1967, Swanson et al. 1990). In the absence of catchment disturbances, variation across the broad landscape is more or less consistent in a relative sense (the coolest catchment in a basin is apt to be coolest every year), but vary in an absolute sense depending on interannual climatic conditions. The relative temperature of a basin can be altered, however, by catastrophic disturbances (e.g., large fires, volcanic eruptions, industrial land use, river regulation) that effect the hydrology, sediment budgets, morphology, or other factors controlling heat dynamics within a stream (Beschta and Taylor 1988, Dauble 1994, Holtby 1988, see also Jensen 1987, Li et al. 1994, Poole and Berman in press). Historically, salmonid populations have required robust in spite of these disturbances because of salmonids' extensive distribution throughout streams and rivers in the Pacific Northwest (Lichatowich 1999). When conditions in one basin or region were rendered inhospitable by catastrophic disturbance, adjacent basins or regions acted as refuges from which salmonids could recolonize disturbed regions after the regions recovered. The extensive distribution of salmonids across the Pacific Northwest has stemmed in part from the development of different life history strategies; the diversity of strategies allows for a broader geographic distribution. Therefore, maintaining the diversity of life history strategies is ultimately critical for long-term population survival viability in the face of unpredictable habitat dynamics (including stream temperature) across the landscape.

At an intermediate spatial scale, temperature trends downstream may exist in streams due to predictable changes (sensu Vannote et al. 1980) in the exchange, processing, and transport of heat within the river (Poole and Berman In press). In many streams today, in the summer, there is downstream heating; the stream starts out at sourcewater (e.g., groundwater, snowmelt) temperature and may eventually reach a higher temperature equilibrium (Sullivan and Adams 1991). However, there are exceptions to this generalization and there is considerable debate as to whether current rates of downstream warming are "natural" or a function of anthropogenic (human-caused) influences. Regardless of the cause, however, where downstream heating occurs, headwater streams provide cool-water refuge for salmonids during warm summer months (Roper et al. 1994). From the perspective of migration, warmer lower reaches of streams can create seasonal "blockages" of access between the stream headwaters and the ocean. Clearly, the timing of salmonid passage must correlate seasonally with hospitable temperatures in the lower reaches.

Similarly, regardless of the presence or absence of downstream patterns of cool-water warming, variation in water temperature between stream segments is present in most stream systems. This creates patterns of alternating warmer and cooler water along any general downstream profile (Figure 6). These patterns typically result from changes along the stream in the configuration of its streambed (Coutant 1999, McCullough 1999, Torgersen et al. 1999) or condition of its banks (Storey and Cowley 1997, Theurer et al. 1985, Zwieniecki and Newton 1999). Where stream temperatures approach or exceed stressful levels, the patches of cool water along the stream provide "oases" where fish and other mobile organisms can avoid stressful temperatures (Berman and Quinn 1991), whether during migration or for residence.

At fine spatial scales such as within a single stream reach, stream temperature can vary substantially based on the localized configuration of the stream such as pool/riffle sequences, variation in the streambed created by large wood, and presence of side-channel and off-channel aquatic habitats (Beschta et al. 1987, Evans and Petts 1997). Similar pockets of cool water exist where small, cold tributaries enter larger streams. Where habitat is diverse and complex, stream characteristics that influence water temperature (water velocity, water depth, shade, and groundwater influence) are highly variable, thereby creating a mosaic of thermal habitat from which salmonids can select (Kaya et al. 1977). On alluvial floodplains, off-channel, side-channel, and springbrook habitats can provide markedly different thermal regimes both spatially and temporally (Cavallo 1997). These small-scale variations in stream temperature can create excellent habitat in streams where habitat might be otherwise marginal. In stream reaches with an array of temperatures suitable for salmonids, juvenile salmonids can to find sites that simultaneously provide cover from predators and water temperatures ideal for growth. Similarly, resident or migrating salmonids can take refuge in cold-water pockets during warm afternoons and take advantage of other habitats during cool night and early morning hours. In short, structural habitat variability at this scale creates thermal microhabitats that fishes can use to avoid elevated water temperatures or to maximize metabolic efficiency, especially during rearing or as adults by holding in deep pools (Coutant 1999, McCullough 1999). Thus, within a stream reach, thermal variability across the range of temperatures suitable for salmonids allows individual fish to select optimal water temperatures for growth, foraging, or other activities on a daily or even hourly basis.

What human activities can affect temperature regimes?

A variety of human activities can influence water temperature regimes, including clearing and developing land, dredging or straightening streams, grazing, and other land use activities. Because water temperature regimes are influenced by factors external to the stream (drivers) (Table 1), structures within the stream (Table 2), and the amount of water flowing in the stream, any human activity that alters these factors, structures, or stream flow can have an effect on stream temperature. Table 5 lists the process that affect stream temperature and the human activities that can alter those temperatures. Figure 3 shows a schematic representation of the variety of complex interactions that ultimately could result in warming of summertime maximum temperatures.

What were historical temperature regimes like? How have temperature regimes changed over time?

There are very few direct data that could be used to describe temperature regimes that might have existed before European settlement in the Pacific Northwest. Sporadic data collected by early European inhabitants of the Pacific Northwest are inadequate to describe historical temperature dynamics.

It is useful to study streams in National Parks and other areas where few human alterations have occurred. The stream temperature regimes there can be used as models against which to compare streams altered by human activities (e.g., Hatten and Conrad 1995, Johnson and Jones 2000). But pristine streams are relatively few in number and are limited primarily to high-elevation headwater streams. Beyond the locality in which a given pristine system occurs, it is difficult to determine whether the same temperature regime might have occurred in another given stream that has been altered by human influences. Similarly, we have no examples of very large pristine rivers in the Pacific Northwest, and thus have no pristine examples of temperature regimes in the Snake or Columbia Rivers, for instance.

Computer models can be used to estimate historical temperature conditions by simulating river temperature, in which human effects on the system have been removed. This can work well to answer some questions, but the limitations inherent in models often make this approach inappropriate. First, models do not consider all of the stream dynamics that affect stream temperature. A model might be able to simulate the effects of restoring riparian vegetation to

Table 5. Mechanism and influences of human influence on channel water temperature

Process / Implication	Influence and Mechanism
Reduced phreatic groundwater discharge results in reduced assimilative capacity	Removal of *upland vegetation* decreases infiltration of groundwater on hillslopes and reduces baseflow in streams. Pumping *wells* for irrigation or municipal water sources can reduce baseflow in nearby streams and rivers.
Reduced stream and tributary flow during low-flow periods reduces assimilative capacity	*Water withdrawals* reduce baseflow and draw down the watertable in the alluvial aquifer. *Dams* alter the flow regime of a river. Removal of *upland vegetation* results in flashy stream flow. *Dikes and levies* confine flows that would otherwise interact with the floodplain and recharge the alluvial aquifer.
Simplified alluvial system structure reduces assimilative capacity by reducing hyporheic flow.	*Dams* reduce peak flows, preventing rejuvenation of alluvial aquifer structure. Removal of *upland vegetation* increases fine sediment load which clogs gravels and reduces hyporheic exchange. *Dikes and levies* confine peak flows which eliminates floodplain inundation and rejuvenation of alluvial aquifer structure; channelization severs subsurface flow pathways. *Riparian management* may remove large woody debris (and its sources) that contributes to streambed complexity.
Simplified channel morphology reduces hyporheic flow thereby reducing assimilative capacity; wider, consolidated channels are less easily shaded and have greater surface area leading to increased heat load	Removal of *upland vegetation* increases peak stream power and/or increases sediment volumes altering the interaction between water and sediment regimes and changing channel morphology. *Dams* remove peak flows that maintain channel morphology *Dikes and levies* confine flood flows that maintain channel morphology and decrease subsurface floodwater storage and, therefore, reduce groundwater discharge during baseflow periods. *Riparian management* may remove large woody debris (and its sources) that contributed to streambed complexity.
Reduced riparian vegetation reduces shade and increases heat load.	*Riparian management* may reduce shade to the channel and may reduce the amount of air trapped by the vegetation, increasing convective and advective heat transfer from the atmosphere to the riparian zone and stream surface.

Source: Poole and Berman in press.

pristine conditions, but lack the ability to adequate address the influences of groundwater and hyporheic flow. Therefore, the model might be appropriate for some streams but not others because of differences in dominant controls on temperature in the stream (Table 3). Similarly, there can be no "uniform" application of a model that will provide consistent, high-quality predictions. Model predictions are only as good as the assumptions and data that go into the model and the way in which the model is applied. At times, tenuous assumptions and lack of data can result in unacceptable levels of uncertainty associated with model predictions.

In short, it is generally impossible to identify the historic temperature regime of a specific stream. Through comparative studies and models, we can make educated guesses about historical regimes with varying levels of confidence depending on the circumstances.

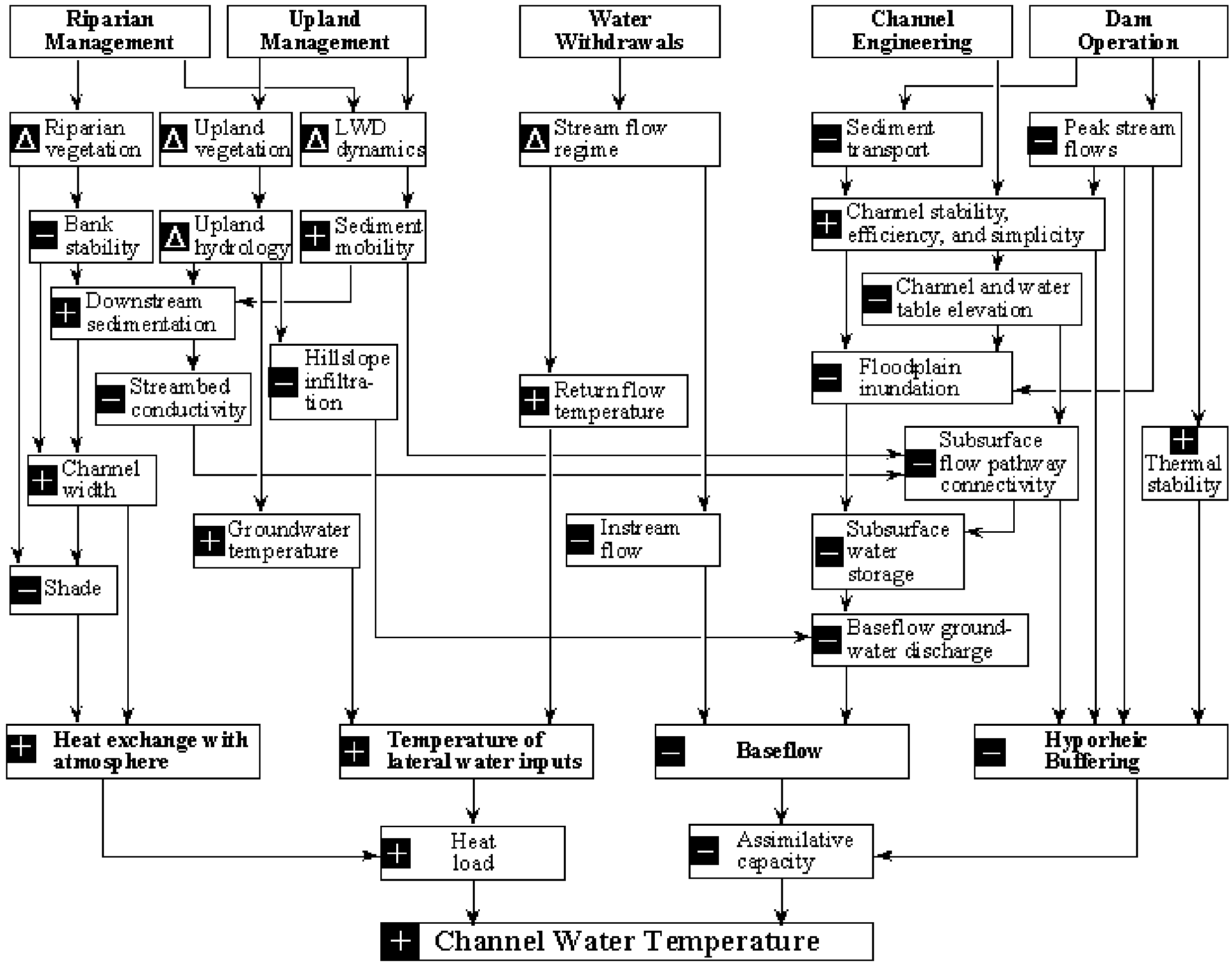

Figure 3. Potential pathways of human-caused warming of stream channels (from Poole and Berman in press).

If we do not know what historical temperature regimes were like, how do we know modern stream temperature regimes are different from the past?

In some instances, studies have been able to document or show strong inference for changes in stream temperature by either successfully establishing expected historical temperature regimes, through adequate or appropriate application of models, or based on long-term monitoring records (e.g., Johnson and Jones 2000, Theurer et al. 1985). Models consistently show that a loss of streamside vegetation (forest harvesting, grazing, conversion to agriculture, urban development, etc.) results in increased summertime maximum temperature. Existing extensive land use impacts to riparian areas suggest that temperatures today are generally higher than historical temperatures.

Studies have shown that variation in channel conditions results in a high diversity of stream temperatures within individual stream reaches (Brown 1997, Cavallo 1997, Frissell et al. 1996), yet many human activities clearly cause simplification of stream channel conditions. Because streams with high channel complexity exhibit high thermal diversity, and because stream complexity has been markedly reduced in many rivers and streams in the region (e.g., Sedell and Froggatt 1984), it follows that thermal diversity at the habitat scale has been markedly reduced from historical conditions.

Finally, historical accounts of salmonids in the Pacific Northwest document that salmonids were well distributed and abundant across the region (see Distributions Issue Paper). Although many factors have contributed to this decline, the historical distribution of salmonids shows that water temperature regimes were sufficient to support healthy salmon populations in most of the streams and rivers of the Pacific Northwest. Laboratory and field studies have allowed us to establish stressful and lethal temperature thresholds for many different salmonids (see Physiology and Behavior issue papers). In spite of the fact that rivers historically must have provided suitable thermal habitat for salmonids, the large rivers and the many of their major tributaries regularly exceed water temperatures shown to be stressful, harmful, or even lethal to salmonids. This implies that thermal regimes in many rivers today are different (warmer) than they once were.

How can temperature regimes respond to human activities?

Changes in stream temperature regimes do not necessarily result in uniform changes in water temperature. Instead, more subtle changes in stream temperature regimes may result from changes in temperature extremes or in temperature variation (Figures 4 and 5). These changes are important because salmonids can lose small-scale temperature refuges during periods of thermal stress. Similarly, changes in the timing of maximum and minimum temperatures can occur (Figure 5, lower left) with or without associated changes in the magnitude of maximum, minimum, or mean stream temperature. These phase changes could be problematic for salmonids because of the delicate timing of salmon migration according to suitable water temperatures.

Although riparian shade may become a less important insulator of water temperature as a river becomes larger (Adams and Sullivan 1989), riparian vegetation still has an important role in affecting the temperature regime of a large river. In large rivers, riparian vegetation (both living vegetation and dead large woody debris) creates channel complexity and habitat diversity (Sedell and Froggatt 1984, Triska 1984) that result in a diversity of thermal environments in the river (Beschta et al. 1987). Furthermore, erosion of stream banks is the primary source of large wood. Therefore, riparian vegetation can be important in temperature regulation and habitat quality even on streams that are not effectively shaded by the vegetation.

Specifically, how can human actions affect temporal regimes?

In general, human activities that result in impacts from multiple sources (non-point sources) tend to simplify the physical structure of aquatic systems, thereby eliminating natural thermal buffers and insulators (Poole and Berman in press). These activities often directly or indirectly simplify the structure of stream channels or riparian zones. Which increases the temporal variability in stream temperature. Daily, seasonal, and interannual temperature ranges all increase with the loss of temperature buffering and insulating processes from streams, because maximum temperatures would be higher and minimum temperatures lower.

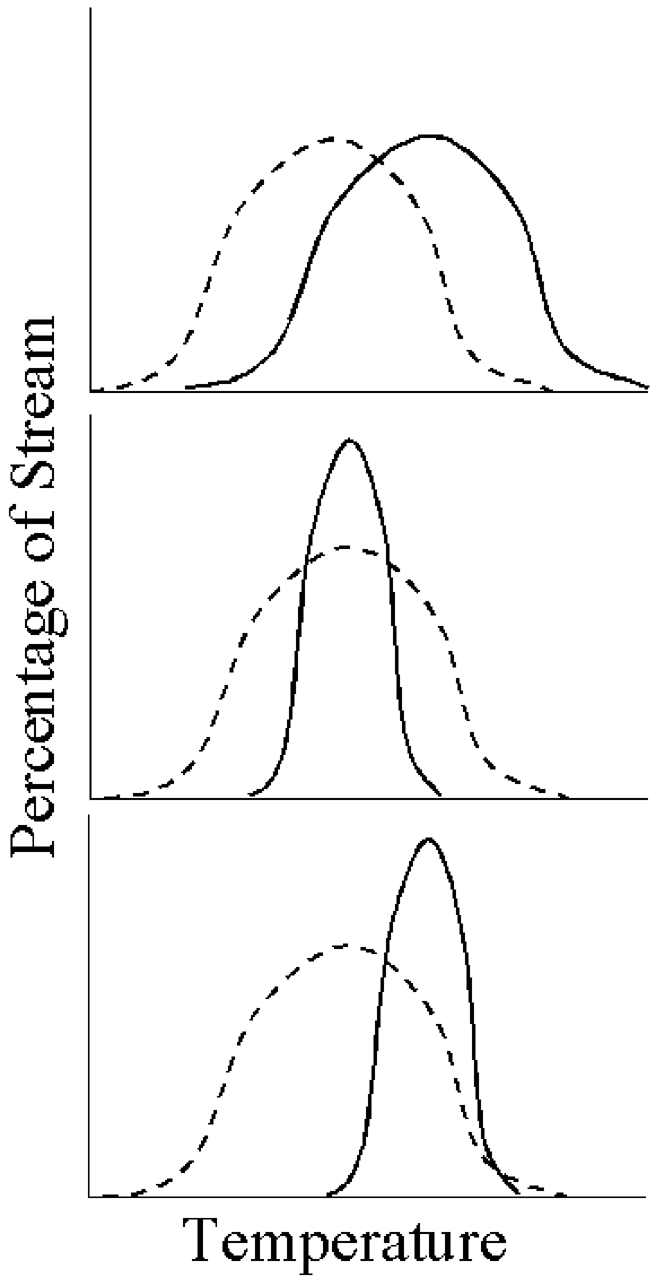

Figure 4. Illustration of potential stream temperature response to human land-use activities. Graphs represent hypothetical distributions of temperature at a given point in time within a single stream segment. Predisturbance ("natural") temperatures are shown with dashed lines; various potential shifts in temperature distribution resulting from human disturbance are shown with solid line. Different temperature responses include a shift in the entire distribution (top), a change in the variation in stream temperature (middle). Note that the combination of these effects (bottom) can result in drastically altered thermal distribution and substantial habitat loss without having temperatures that exceed the "range of natural variability."

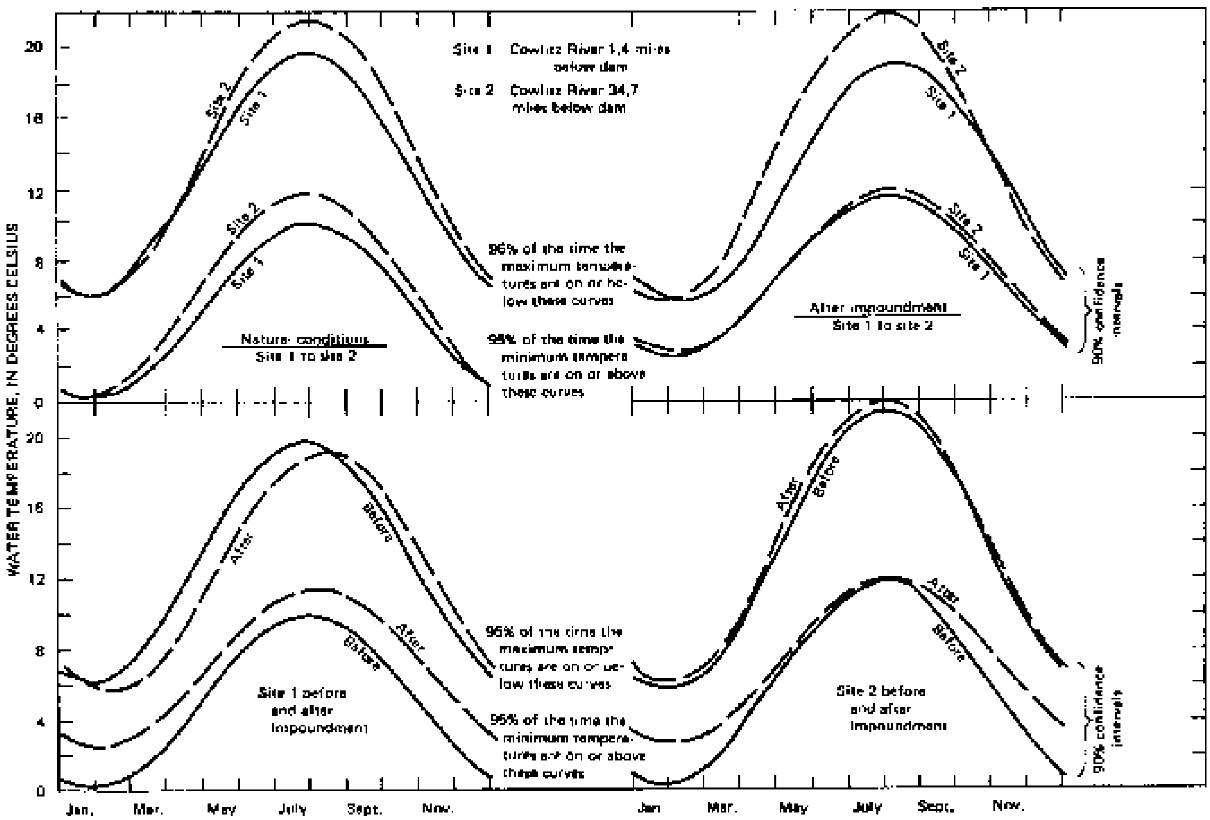

Figure 5. Effect of water impoundment on stream temperature, Cowlitz River, Washington. Graphs show the 95% confidence intervals about the maximum and minimum stream temperatures for natural and controlled conditions at two stream-temperature measuring sites below Mayfield Dam (from Collins 1973).

The amount of temporal variation in stream temperature depends on the relative importance of various buffering and insulating processes, which is determined by the physical characteristics of the stream (Table 3). In small streams where canopy cover is a dominant insulator, daily variation in stream temperature can be increased by removal of riparian vegetation (Beschta 1997). Similarly, where groundwater is an important buffer to stream temperature, change in the character of the groundwater temperature (Hewlett and Fortson 1982) or flow dynamics (Poole and Berman in press) may substantially increase seasonal variation in water temperature. Similarly, interannual variation in stream temperature can be altered by anthropogenic or natural year-to-year differences in climate and stream discharge.

Significant anthropogenic point sources that release water at a constant temperature throughout the year tend to stabilize stream temperature over time. Rivers downstream from hypolimnetic release dams (those drawing water from the bottom of the reservoir) and industrial cooling facilities can lessen thermal variability across all temporal scales because of the influence of the flow source's constant temperature. If the temperature of the dam releases (or other flow sources) is within the biological tolerances of aquatic communities, dams can actually contribute to cold-water habitat. However, even in such cases, the diversity of aquatic communities below dams can be reduced (Ward 1984). If the temperature of substantial flow sources is outside the biological tolerance of an aquatic species, the resulting thermally homogenized stream reaches no longer provide suitable habitat and become thermal barriers to the migration of the species.

What about spatial regimes—how can human actions affect these?

At coarse spatial scales, human activities have likely increased the variability in stream temperature across catchments. Usually, this increase in temperature variability results from converting land for industrial land use or developing floodplains for agricultural or urban land use (National Research Council 1996). These activities tend to interrupt processes that are important buffers and insulators of water temperature (Poole and Berman in press) such as riparian shade and ground- and surface-water exchange. Streams impacted by such processes are classified as developed streams, and streams untouched by human activities are classified as pristine. Within each class, average stream temperature in a basin is a function of the basin characteristics (Poole and Berman in press), but as a group developed basins are warmer than pristine basins (Hatten and Conrad 1995).

Few studies have been conducted comparing historic temperature patterns with current patterns at the intermediate spatial scale of stream segments, but we can postulate that the distribution of average summertime temperatures across stream segments has changed since pre-European settlement. There are historical data (e.g., Murphy and Metsker 1962) suggesting that, with specific geomorphic or climatic contexts, some stream segments in the Pacific Northwest may have been susceptible to warming beyond the thermal tolerances of salmonids. Also, stream segments may have warmed in the past after natural catastrophic basin disturbances (Huntington 1998). However, there has likely been an increase in the percentage of stream segments where these unsuitable temperatures occur and in the duration of these high temperatures (Hatten and Conrad 1995).

Additionally, there has likely been a shift in the spatial distribution of stream temperatures across segments. The diversity of thermal buffering and insulating processes that occurs along a downstream profile of streams results in a patchy distribution of temperature at the stream segment scale (Torgersen et al. 1999). Yet human land use and development in stream catchments have a tendency to homogenize and remove insulating and buffering processes along streams (Coutant 1999, Poole and Berman in press), thereby increasing the rate at which water temperature equilibrates with local conditions (sensu Sullivan and Adams 1991). Recent evidence suggests that the rate of downstream warming is a function of catchment conditions, local geomorphic setting, and local riparian conditions of the stream (Torgersen et al. 1999). In the last century, massive geomorphic alteration of lowland river systems has occurred by various human land uses, including logging, grazing, and mining (Lichatowich 1999); floodplain development, diking, and riparian logging (Lichatowich 1999, Sedell and Froggatt 1984); removal of large wood (Triska 1984); channel "improvements" to aid river navigation (Sedell and Luchessa 1982), and decimation of historical beaver populations (Lichatowich 1999). These geomorphic alterations have severed the ecological connections between rivers and their floodplains (sensu Ward 1998), thereby disrupting important buffers of water temperature in lowland systems including the exchange of groundwater and surface water and the shading influences of gallery forests on lowland floodplains (sensu Poole and Berman in press). Thus, equilibrium stream temperatures have likely been altered by human activities since the advent of Euro-American settlement.

In many degraded systems, downstream warming (Adams and Sullivan 1989, Zwieniecki and Newton 1999) has been exacerbated by historical changes in channel morphology and riparian condition that alter important natural temperature buffers and insulating processes (Poole and Berman in press). Therefore, although some downstream warming may be expected under pristine conditions in many streams, human activities have likely shifted the distribution of cool water along the downstream profile (Theurer et al. 1985). Where alternating warmer and cooler segments once occurred, streams now exhibit a "cool in the headwaters/warm at the mouth" pattern (e.g., Figure 6). This loss of cool water habitat in the lower reaches of streams represents a loss of lowland cool-water habitat for rearing and residency (Meisner 1990, Theurer et al. 1985) as well as a formidable barrier to upstream migration because of the reduction in potential cool-water staging areas.

At fine spatial scales, human-caused disruptions of processes that build and maintain structural habitat diversity have drastically reduced thermal variability of streams. Structural diversity within stream reaches consits of topographic variation within the main channel as well as the presence and accessibility of side- and off-channel habitats (Cavallo 1997). Structural diversity creates a diverse set of associations between water velocity, water depth, shade, and groundwater influence (Abbe and Montgomery 1996, Beschta and Platts 1986, Cavallo 1997, Harvey and Bencala 1993, Nakamura and Swanson 1993). This diversity of associations creates a range of thermal environments from which fish can select (Bilby 1984).

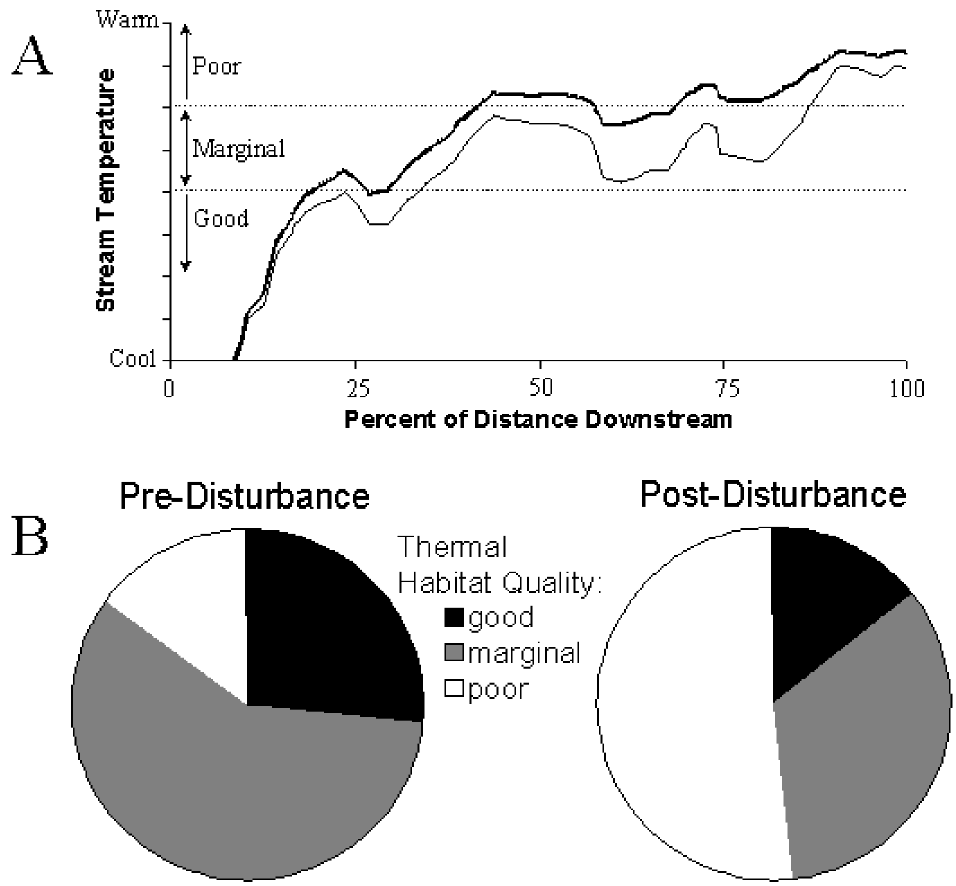

Figure 6. Quantitative depiction of results from a conceptual model of stream warming. (A) Thinner "pre-disturbance" line represents historic downstream temperature trend; thicker "post-disturbance" line represents the effects of a hypothetical change in stream structure that results in a cumulative 2.5% increase per stream km in the rate at which water approaches an assumed equilibrium temperature of 22.5° C. Zones demarcated by dashed lines show associated habitat quality of a hypothetical species of concern. (B) Resulting change in thermal quality of habitat after the hypothetical structural change (after Poole and Berman in press).

What are cumulative effects? Are stream temperatures cumulative? Can cumulative effects influence temperature regimes?

Bisson et al. (1992) define cumulative effects as follows:

[T]he term cumulative effects has been implicitly or explicitly taken to mean the repeated, additive, or synergistic effects of forestry or other land-use practices on various components of a stream environment over space and time (Burns 1991). The term suggests that environmental impacts of specific management activities cannot properly be viewed in isolation from a broad perspective of land management at large spatial scales and long time scales.

It is generally agreed that cumulative effects, although at times difficult to document, are a reality. Although a recent study (Zwieniecki and Newton 1999) concluded that heat added to streams is not cumulative, the study is not compelling,[1] especially given substantial evidence (described next) showing that human impacts on stream temperature are cumulative.

There are at least three different mechanisms by which human impacts on stream temperature are cumulative in effect. The first mechanism is the repeated, additive localized effects on stream reaches directly adjacent to land use activities. Because land use activities have localized effects on water temperature, the effect of an activity on the stream is proportional to the percentage of the stream affected by the land use. For instance, where 10% of a stream's length is affected by a given land use, 10% of the stream will be affected by localized effects on stream temperature regimes. Where 90% of the stream is affected by the land use, 90% of the stream will suffer localized degradation of stream temperature regimes. In this sense there is without question a cumulative effect of land use on thermal regime.

The second mechanism of cumulative effects is the downstream accumulation of heat that may accompany changes in land use. If one considers the entire stream course, a stream may exhibit a downstream warming trend in temperature (e.g., dashed line in Figure 6A). Along this trend, however, there may be short zones where stream temperature drops, usually because of the influence of riparian vegetation, groundwater, topographic shade, or tributaries entering the stream. The downstream rate of temperature change can be accelerated by land use activities. Accelerating the rate of downstream warming, however, will not necessarily remove the small zones of downstream cooling. Instead, the stream temperature may simply rise without losing the overall temperature pattern along the stream course (Figure 6). Figure 6 represents a potential accumulation of heat in the stream along the stream course and thus a potential mechanism of cumulative effects on stream temperature.

There is considerable debate about whether added heat accumulates streams or dissipates from streams as water flows downstream. Where downstream heat dissipation occurs, there is further debate over the distance needed to dissipate added heat. Sugden et al. (1998), Caldwell et al. (1991), and Zwieniecki and Newton (1999) argue that little of the heat added to small headwater streams is transported downstream and that short sections of functional riparian zones are sufficient to prevent accumulation of heat in streams. The data used to support these conclusions, though, show high variability in the effectiveness of short riparian buffers, suggesting that streams differ with respect to their heat dissipation rates (see Appendix for further discussion). Also, these studies do not address additive (described previously) or multiplicative cumulative effects (described below) such as the fact that basin land use may lead to subsequent disturbances (e.g., landslides) that ultimately affect the accumulation of heat in a stream (Johnson and Jones 2000).

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[1] One recent study (Zwieniecki and Newton 1999) purports to address cumulative effects of timber harvest on stream temperature and concludes that "There appears to be no basis for a cumulative effect on temperature from multiple harvest units interspersed with forested stream sections." Although the design of the study and the authors' conclusions are controversial, the study has been widely circulated. The Appendix explains how the study design may have been flawed and provides our rational for rejecting the authors' conclusions *regarding cumulative effects*. We do not, however, reject all of their data.

Where water receives heat from upstream sources and flows downstream, its temperature will adjust towards the temperature of the downstream environment. Thus, added heat may dissipate from a stream if downstream conditions facilitate dissipation. Any heat that does not dissipate will be transported downstream. The distance over which heat is transported downstream depends upon the flow volume, flow velocity, groundwater interactions, groundwater temperature, air temperature, channel morphology, riparian vegetation, and many other conditions. Thus, under some circumstances, upstream heating may affect conditions only tens or hundreds of meters downstream. In these circumstances, downstream accumulation of heat may not be a problem. In other circumcstances, the heat may be transported in the stream for many kilometers and therefore may contribute to a downstream accumulation of heat. At either spatial scale, however, the effect of elevated water temperatures extends some distance downstream from the place where the heat was added. Thus, when replicated over the landscape, any added heat can contribute to cumulative effects via repeated, additive localized effects (i.e., the first mechanism described above).

The third mechanism of cumulative effects may be very widespread but poorly documented or understood: multiplicative (or synergistic) effects from the same land use compounded by natural disturbances. For instance, removal of riparian vegetation may simultaneously affect stream shade, stream width, sediment sources, and channel stability in a stream (Salo and Cundy 1987). Localized effects may be the only initial influence, but as land use intensity increases, processes such as sediment delivery to the system may increase incrementally (Cedarholm et al. 1981, Huntington 1998, Megahan et al. 1992, Reid and Dunne 1984). Fine sediments can coat the streambed with a blanket of less transmissive sediments (Eaglin and Hubert 1993, Huntington 1998) thus reducing hyporheic flow (Schälchli 1992) and associated temperature-buffering capability. Eventually, as land use intensity further increases, channel stability is reduced to the point where, during heavy precipitation, mass wasting substantially alters the streambed and channel banks (Cedarholm et al. 1981), or the entire channel is destabilized and a torrent of debris scours the channel down to the bedrock (Johnson and Jones 2000). As a result, even in those portions of the stream not experiencing localized influences from land use, the entire hyporheic zone can be disrupted or lost, the channel may be widened, and riparian vegetation may be reduced or eliminated from the stream banks. For instance, Johnson and Jones (2000) reported that temperature response to a debris flow caused by catchment roading and patch-cutting was similar to temperature response to clearcutting in headwater streams. Effectively, intensive land use creates the circumstances under which natural disturbances result in unnatural disruption of the stream structures and processes that buffer and insulate water temperature.

Thus, the concept of cumulative effects is important to our understanding of the effects of human activities on water temperature.

What are the implications for salmonids of alterations to thermal regimes?

A substantial body of evidence exists about the effect of stream temperature on the physiology of various salmonid life stages (see Physiology Issue Paper). Stream temperature can directly and indirectly affect the growth and/or mortality rate of every freshwater life stage (Groot et al. 1995). Therefore, it follows that anthropogenic increases in mean or maximum stream temperature can substantively influence the viability of salmonid populations. Diversity in thermal conditions is important in maintaining salmonid populations, but the role of thermal diversity is not easily described.

The direction and magnitude of changes in the temperature variation will affect salmonids differently depending on whether the changes affect spatial or temporal variation and depending on the scale of the change. As shown by the following examples, human activities often alter different types and scales of thermal variability in ways that affect fish synergistically rather than in ways that might help mitigate adverse affects.

Where daily (fine-scale temporal) variation in stream temperature is high, salmonids are apt to face stressful or lethal temperature for part of the day. During times of peak summertime water temperature in some streams, only a small percentage of thermal habitats may provide adequate temperatures for salmonids. Common anthropogenic impacts (especially non-point source impacts) typically increase fine-scale temporal variability while decreasing fine-scale (within-stream reach) spatial variability. In the Pacific Northwest, the combination of decimation of beaver populations (Lichatowich 1999), alterations to large wood dynamics (Sedell and Froggatt 1984; Triska 1984), removal of riparian vegetation (Li et al. 1994; Theurer et al. 1985), floodplain development (National Research Council 1996; Sedell and Luchessa 1982), and channel engineering (to facilitate navigation, flood control) (National Research Council 1996; Steiger et al. 1998) has resulted in drastically simplified streams that can support only a fraction of historical thermal diversity within reaches. Given the propensity of salmonids to seek appropriate thermal habitat (Berman and Quinn 1991), this loss of fine-scale spatial diversity forces fish to move greater distances to seek appropriate thermal habitats or, worse, prevents the selection of appropriate habitat altogether by eliminating it from the stream.

Similarly, seasonal (intermediate-scale temporal) variation in temperature can create seasonal thermal barriers to salmonid in- and out-migration. Historically, salmonids used daily stream temperature variation in combination with intersegment variation (intermediate-scale spatial variation) to bypass thermal barriers. Individual fish tend to migrate through thermal barriers at night (when water temperatures are cooler) and then "stage" during the day in stream segments between the thermal barriers where stream morphology encourages processes that buffer or insulate water temperatures and provide cool water throughout the day. Not only has human alteration of catchment hydrology altered temporal variation by allowing streams to warm sooner and creating thermal barriers earlier in the year, channel "improvements" (dredging, diking, rip-rap, etc) have altered spatial variation by changing floodplain morphology and riparian vegetation conditions, which, in turn, reduce the size and frequency of intervening cool spots in the stream.

Finally, the effects of coarse-scale temporal variability driven by climate and catastrophic disturbance were once tempered by the existence of large areas of appropriate and well-connected habitat because, regardless of the specific conditions in a given year, good habitat was accessible somewhere within a basin. Again, humans have not only increased the coarse-scale temporal variation (e.g., by drawing more water out of streams during dry years) and exposed salmonids to extremes beyond the normal range of variation, we have increased the coarse-scale spatial variation within basins by fragmenting and eliminating the large, well-connected tracts of high-quality thermal habitat. Increased thermal variability across basins has occurred primarily by increasing the mean summertime temperature of individual streams while other streams have remained relatively unaffected. This increased coarse-scale variability means that any two adjacent basins are now less likely to provides suitable thermal habitat than in the past. Therefore, the average size of and connectivity between suitable habitat patches has been reduced. The resulting habitat fragmentation has been shown to influence salmonid population structure and persistence (Dunham and Rieman 1999). Among other things, fragmented populations are less resilient to coarse-scale temporal variation in habitat conditions (including stream temperature).

Summary

Water temperatures in Pacific Northwest streams are variable over space and time. Although the concept of a temperature regime is useful for describing stream temperatures, stream temperature regimes are highly complex, partly because they are affected by an array of variable external factors and internal stream structures. Salmonids have adapted to historical temperature regimes through the evolution of a variety of life history strategies and therefore depend on appropriate temperature regimes over time. Although human activities have affected stream temperature regimes in a variety of ways depending on the type of activity and the scale at which temperature regimes are measured, increases in summertime temperatures have been common. Many of the human-caused changes in temperature regime have been detrimental to salmonid populations because they have resulted in large changes in temperature regimes in relatively short periods of time. If our goal is to restore salmonid populations, management of stream temperature may need to focus on the goal of restoring temperature regimes that are compatible with desirable population levels for native salmonids.

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Appendix

A Comment on "Influence of Streamside Cover and Stream Features on Temperature Trends in Forested Streams in Western Oregon" by M. Zwieniecki and M. Newton

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Zwieniecki and Newton (1999) published a study, "Influence of Streamside Cover and Stream Features on Temperature Trends in Forested Streams in Western Oregon," in which stream temperatures in small headwater streams were measured at the upstream and downstream end of stream reaches, where riparian vegetation was removed from the stream banks ("harvested reaches"). Water temperatures were also measured 150 and 300 m further downstream, where the stream flowed under riparian vegetation (i.e., below "recovery zones"). The intent of the study was to test whether heat added to the system in the harvested reaches persisted through the recovery zone or whether the recovery zone was sufficient to dissipate the heat. The study used 7-day moving mean maximum water temperature as an indicator of stream temperature and compared measured temperature at the bottom of recovery zones with predicted "pre-logging" water temperatures derived from temperature normagraphs (plots of downstream warming trends in the streams; see also Adams and Sullivan 1989; Sullivan et al. 1990; Zwieniecki and Newton 1999). If heat added to streams in the harvested reaches persisted in the streams, the authors predicted that streams' maximum temperatures would be warmer at the bottom of the recovery zone than the predicted temperatures derived from the normagraphs. If the heat did not persist but was instead dissipated, the authors predicted that the streams' temperatures at the bottom of the recovery zone would return to the predicted temperatures.

Consistently in the harvested reaches, stream temperature warmed, likely due to the lack of shade from riparian vegetation. In recovery zones, however, the data showed highly variable responses. In some streams, the water temperature cooled in the recovery zone, sometimes to well below the expected temperature. In other cases, water did not cool to the expected temperature in the recovery zones. In 2 (out of 14) cases, water temperatures increased in the recovery zone. On average, the water temperature at the bottom of the recovery zone was approximately equal to the expected temperature estimated from normagraphs.

In order to test whether influxes of cool groundwater (rather then energy dissipation) were responsible for the cooling trends in some recovery zones, the authors postulated that "the maximum temperature in the recovery zone should have appeared after the maximum showed up at the downstream edge of the harvest unit, reflecting the time needed for the water to flow [that distance]." Since the average lapse for peak temperatures was only "a fraction" of the required travel time, the authors ruled out groundwater dilution as the cause of water cooling in the recovery zone.

Although the amount of thermal "recovery" that occurred in recovery zones varied widely across the streams, the interstream mean difference between expected and measured stream temperatures was not significantly different from zero. Thus, the authors conclude that, on average, streams flowing under a closed canopy rapidly dissipate heat energy gained in reaches with harvested riparian zones. Because groundwater dilutions were ruled out as the cause of cooling trends, the authors "reject[ed] the hypothesis that harvesting, with modest buffers and even gaps, leads to an accumulation of heat that persists more than 300 m below the harvest unit." They further concluded that "[t]here appears to be no basis for a cumulative effect on temperature from multiple harvest units interspersed with forested stream sections."

Although compelling on the surface, the experimental design of this study may be fundamentally flawed in the following ways:

1. The normagraphs used to predict downstream temperatures are not sufficiently accurate for their application in this experiment. In an evaluation of such normagraphs, Sullivan et al. (1990) concluded "the normagraphs could be used as a quick index of probable changes in temperature at different

watershed locations. However, the method was not accurate enough on a site-by-site basis to correctly identify temperature with sufficient precision for regulatory purposes." In light of the high variability in temperature trends in recovery zones, the normagraphs should not have been used to predict preharvest stream temperature at the bottom of the recovery zones. Preharvest conditions would have to be measured before harvest occurred in the basin. Since there were no accurate measures of expected preharvest downstream temperatures, the conclusion that stream temperatures below the recovery zone are not warmer than preharvest conditions cannot be drawn.

2. Even if the normagraph prediction are considered to be accurate representation of the preharvest conditions, the data do not consistently allow the rejection of the hypothesis that heat does not accumulate along the stream course. First, of the 14 sites in the experiment, 5 did not cool to the temperatures predicted by the normagraphs and 2 showed warming trends in the recovery zone. Second, the variability in stream temperature response was very large relative to the calculated mean difference between measured and predicted temperature; therefore, the "power" of the statistical test (the likelihood of detecting a real difference between means) would have been very low given the sample size (6 for high-discharge creeks, and 8 for low-discharge creeks). Thus, there would have been a low probability of detecting any real difference between measured and expected stream temperatures. The power of statistical tests can be estimated (Zar 1999), but, according to a personal communication with the second author of the study (M. Newton), the data used in the study are no longer available, so the statistical power of the tests cannot be determined. Therefore, the fact that there was no significant difference reported in the study may be due to insufficient sample size rather than the lack of a real difference.

3. The authors' attempt to rule out groundwater dilution as the source of stream cooling is flawed. The authors' prediction about the lag time between upstream and downstream peaks in water temperature is based on a simplistic conceptual model of "one-way" groundwater flow from the underlying aquifer to the stream. However, hyporheic flow is extremely common in small, forested streams and reflects the two-way exchange of water between the streambed and surface channel. Where hyporheic flow occurs, the heat added to the stream in the harvested units may have been temporarily stored in the streambed and slowly diffused back into the stream over minutes, hours, or days. If hyporheic flow is responsible for the downstream thermal "recovery," the authors' prediction about expected lag times would be falsified because of the exchange of water between channel and hyporheic zone, not because the stream had cooled. If hyporheic flow were responsible for the observed temperature patterns, the overall temperature budget in the stream (including the hyporheic zone) may be accumulating heat. Therefore, the authors' rejection of the hypothesis that heat can accumulate in a downstream direction appears questionable.

4. Even if the time lag prediction is a credible hypothesis test, the data used to calculate the downstream lag time in maximum temperature seem inappropriate. Downstream travel times were described only as "variable" in the study, but a rough indication of stream velocity was given by the authors when they stated that water "in the afternoon at mile 4 of the stream would be ... water that evening at mile 7." If the time difference between "afternoon" and "evening" is somewhere between 6 and 12 hours and water travels about 4.8 km (3 miles) in that time, it appears that average stream velocity was on the order of 400 to 800 m per hour. The electronic temperature monitors used in the study were programmed to sample water temperature every 48 minutes. Thus, it appears that water would travel approximately 320 to 640 m between each successive temperature reading, two to four times the distance (150 m) over which the lag time in maximum temperature was calculated. It seems unlikely that the 48-minute data collection interval was sufficient to provide an accurate estimate of the downstream lag in maximum temperature over a 150 m distance. This would explain, in part, why the range in calculated lag times across streams was surprisingly large (107 to 56 minutes). It further calls into question whether negative lag times used to discount the influence of groundwater in the study were real, or artifacts of an improper sampling design.

5. The study design is inadequate to support the authors' conclusion that "[t]here appears to be no basis for a cumulative effect on temperature from multiple harvest units interspersed with forested stream sections." The authors appear to draw this conclusion by defining "cumulative effects" as "an accumulation of heat

that persists downstream." Relative to published definitions, this is a narrow interpretation of the concept of cumulative effects. For instance, Bisson et al. (1992) describe and provide a reference for the definition of cumulative effects as follows: "[T]he term cumulative effects has been implicitly or explicitly taken to mean the repeated, additive, or synergistic effects of forestry or other land-use practices on various components of a stream environment over space and time (Burns 1991)." Therefore, in forested systems, there are at least three mechanisms of cumulative effects on stream temperature. First is the incremental loss of high-quality thermal habitat resulting from localized effects associated with each additional removal of riparian vegetation. Where riparian vegetation is removed from 10% of the stream channel, 10% of the habitat will be thermally degraded by local effects. Where 50% is removed, 50% will be degraded by local effect. This is an additive cumulative affect not addressed by the study. Second, due to the aforementioned problems with the study design and the reasonable alternative interpretations of the data, the study does not adequately or decisively rule out the downstream persistence of accumulated heat. Third, the study does not address multiplicative (synergistic) cumulative effects on temperature from logging-induced changes in flow regime (Burt and Swank 1992, Harr 1980, Harr et al. 1982, Ziemer and Keppeler 1990), groundwater temperature and flow (Hetherington 1982, Hewlett and Fortson 1982, Meisner 1990), sediment load/channel morphology (Dose and Roper 1994, Knapp and Matthews 1996, Richards et al. 1996, Sidle and Sharma 1996), and large wood dynamics (Hauer et al. 1999, Ralph et al. 1994), all of which result in changes to the hydrologic processes controlling stream temperature in small forested streams (Poole and Berman in press). These synergistic effects are illustrated by Johnson and Jones (2000), who showed that mass wasting (in this case, a delayed, synergistic effect of logging) caused stream warming similar to warming caused by catchment and riparian clearcutting. Finally, Zwieniecki and Newton's study (1999) in no way addresses "multiple harvests interspersed with forested stream sections." The study looks at several replicates of individual harvests, each on a separate study stream. Any potential cumulative effects from upstream were factored out because the data analysis focused on the relative temperature changes within each study reach. Thus, the authors' conclusion that there is "no basis for a cumulative effect on temperature from multiple harvest units interspersed with forested stream sections" appears to outstrip the potential applicability of study findings. An expanded (and more widely held) interpretation of the phrase "cumulative effects" (Bisson et al. 1992) supports the conclusions of Beschta and Taylor (1988) and Gregory et al. (1991): The effects of increased logging intensity on stream temperature are inherently cumulative. In short, conclusions about the cumulative effects of multiple harvests interspersed with forested stream sections are inappropriate unless the study covers the breadth of the accepted definition of "cumulative effects" and the study is conducted on multiple harvests interspersed with forested stream sections.

The Technical Workgroup concludes that the research reported by Zwieniecki and Newton (1999) may be flawed in its design, implementation, or interpretation. Even if it is not flawed, the authors' conclusions about cumulative effects outstrip the scope of the research. The question of thermal recovery below riparian disturbances remains open. Clearly, downstream dissipation of heat energy can occur. Yet, where downstream dissipation occurs, the distance required to dissipate added heat is dependent upon many complex interactions and is site-specific. It is most reasonable to assume that some streams may dissipate added heat over a distance of merely tens or hundreds of meters. Other streams may require many kilometers to dissipate added heat. Still others may never fully dissipate added heat, especially where riparian vegetation and channel morphology have been disturbed along most or all of the stream channel.